Vibration Control of Mechanical Suspension System Using Active Force Control

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Abstract: This paper presents the practical implementation of an active force control (AFC) strategy to a laboratory scaled vibration isolator platform. The research was carried out to investigate the performance of vibration suppression capability of feedback controller using AFC. Two types of controller schemes were examined and compared involving the classic proportional-integral-derivative (PID) controller and AFC scheme. The laboratory scaled physical rig was developed using the MATLAB/Simulink with Real Time Workshop (RTW) tool that is interfaced with a suitable data acquisition card via a personal computer (PC) as the main controller. Appropriate vibration source was modelled and applied to the proposed systems to test for the system robustness. Results obtained in this study verified the potential and superiority of the proposed AFC scheme as a robust active vibration suppressor compared to the other schemes considered in the study.
Keywords: Vibration, suspension system, active force control, robust, real-time.

1. Introduction

Vibration can be pleasant and useful as in massaging and therapeutic application but at the same time it can be unpleasant and harmful too because it can lead to catastrophic failures of components and materials. Unwanted vibration can interfere with our comfort, damage to structures, reduction of equipment performance and machinery noise level. For examples, vibration of car or any other automobile can lead to driver discomfort and eventually fatigue. Electronic component used in automobile or planes, machines, structures and so on may also fail because of vibration [1]. Furthermore, a vibration environment can cause malfunction or failure of mechanical systems and may cause injury to human beings. Therefore, it is envisaged that a form of vibration control or suppressor is needed to compensate the undesirable vibration effect so that it will not damage the systems or cause injury/discomfort to human beings.

Vibration absorber and vibration isolator are two important concepts of vibration control. Vibration isolation is a common method used to protect receivers (device, human, system, machine or structure) from the vibration source. Car suspension system is one example of a system that employs an isolation concept in an effort to reduce the car body displacement due to the road profile. In this context, vibration isolation or vibration 'absorption' is primarily realized by passive methods which deal directly with the physical properties of a mechanical structure itself that is related to stiffness, damping and mass. The performances of the passive systems are highly system dependent as they are unable to adapt or re-tune to changing disturbances or structural characteristics over time [2].

The idea of active control is that desirable performance characteristics can be achieved through cooperating sensors, actuators and control techniques within mechanical structures. Roger et. al [3] has presented the design methodology for active control in their study in which they discussed and proposed on the actuation concept, alternate control algorithm and also about an approach to solving the problem. In the design process section, they have explored actuators and their technologies, controller hardware and software, and sensors to be integrated effectively into the system.

Recently active vibration isolation with various control methods and actuators technology has become a popular topic in vibration control and applied on many systems such as suspension system, precision machine platform, building structures, etcs. D'Amato and Viassolo [4] have designed an active suspension car system using an inner loop to track the actuator's command and outer controller loop used to satisfy the passenger's comfort with the proposed method applied to a quarter car model. Yildrim [5] presented a simulation study with comparison made between PID, PI and PD with the proposed neural network schemes applied to a suspension system. He has shown that the proposed scheme can guarantee the stability of the adaptive system in the presence of the modelling uncertainties. Ahn [6] proposed a hybrid type of active vibration isolation system using a form of neural network in which a hybrid of passive air spring and active electromagnetic actuators was employed. The results of their study indicate that the hybrid model provides a better vibration isolation performance compared to the passive system. A study by Abakumov [7] showed that his proposed scheme using new optimal and quasi-optimal control algorithm for active isolation system has shown an improved and better vibration suppression of the disturbances than the PID counterpart.

This paper presents the practical implementation of an active force control (AFC) strategy to a laboratory scaled vibration isolator platform. The research was carried out to investigate the performance of vibration suppression capability of a feedback controller using AFC. Two types of controller schemes were examined and compared involving the classic proportional-integral-derivative (PID) controller and AFC scheme.

2. Active Vibration Control

An active vibration control is a method that relies on the use of an external power source called actuator (e.g. a hydraulic piston, a piezoelectric device or an electric motor)[1]. The actuator will provide a force or displacement to the system based on the measurement of the response of the system using feedback control system. Based on Fig. 1, an active vibration control system working principle starts with measuring the response of the system using suitable sensors. Then the electronic circuit reads the sensors output, later converts the signal appropriately and sent it to the control unit. Based on the control law used, the calculated force signal is sent to the actuator and the controlled force is correspondingly applied to the system. The actuator force will actually compensate the vibration force in the system.

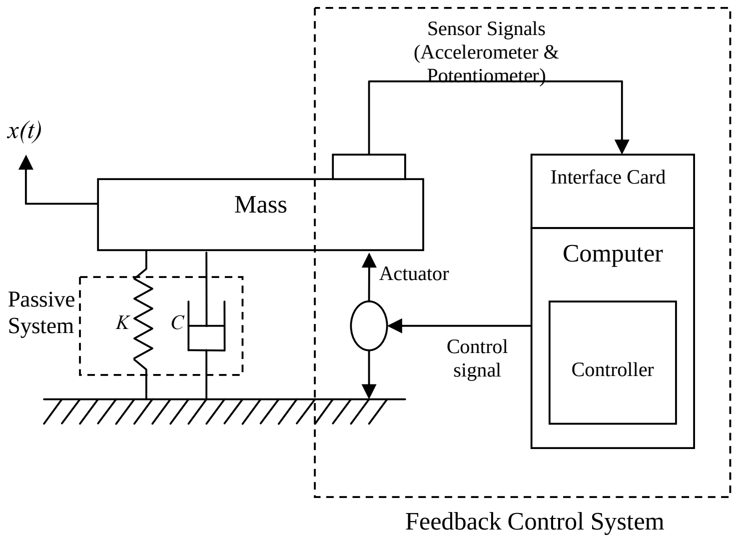


Fig. 1: Active Vibration Control

A typical PID control law that can be used in the active vibration control system is as follows:

$$G_c = K_p e + K_i \int e \, dt + K_d \dot{e} \quad (1)$$

where

G_c	: control signal
K_p, K_i and K_d	: proportional, integral and derivative gains respectively
e and $\dot{e}$	: joint position error and its derivative respectively

It should be noted that a family of PID controllers (P, PI, PD and PID) can be realized by simply exploiting the controller gains. For example, if the integral gain K_i is set to zero, then the controller is reduced to a PD type. However, the PD type controller (or others) can be simply referred to as a generic PID controller for convenience and thus, the PID term is preferred and would be consistently used throughout the paper. In general, active vibration control can be viewed as a method that is based on the use of sensors and actuators within a mechanical structure, cooperating through signal conditioning electronics and control technique [4].

3. Active Force Control (AFC)

Hewitt first introduced Active Force Control (AFC) strategy to control a dynamic system in the late 70s [8]. It has been shown that by using AFC, the system remains stable, robust and effective even in the presence of known/unknown disturbances, uncertainties and varied operating conditions. AFC has been demonstrated to perform excellently compared to the conventional methods in controlling robot arm [9-13].

The essence of the AFC strategy is to obtain the estimated disturbances force, F^* via the measurement of mass acceleration, a and actuator force, F_a together with an appropriate estimation of the estimated mass, M^* as described in the following equation:

$$F^* = F_a - M^* a \tag{2}$$

It is obvious that Eq. 2 is very simple and is expected to be computationally light; this is in fact a very attractive option for real-time or on-line implementation. Fig. 2 illustrates a schematic of an AFC scheme applied to a dynamic system. The physical quantities, which need to be measured directly from the system, are the actuating force, F_a and the acceleration, a which can be obtained using some sensing elements. Then the estimated mass of the system, M^* with the presence of the disturbances (e.g. vibration, friction and changes in the operating conditions) that partially contribute to the acceleration should be approximated appropriately. This can be achieved by using simple crude approximation (CA) method or artificial intelligent (AI) methods [10, 11].

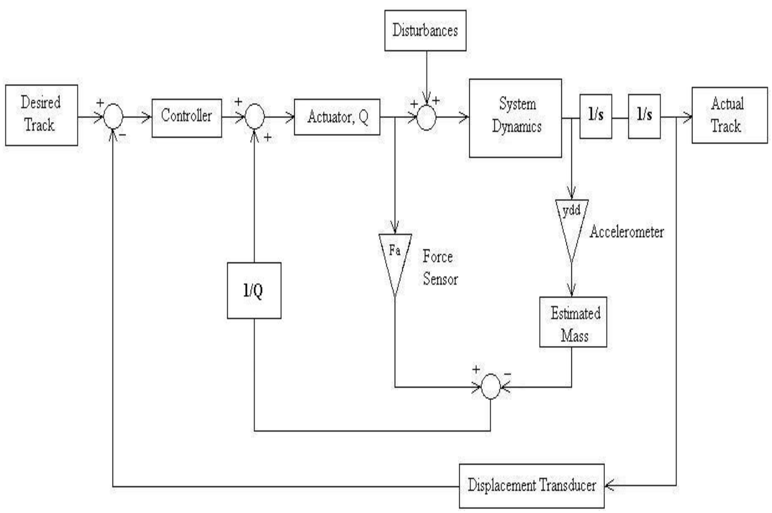
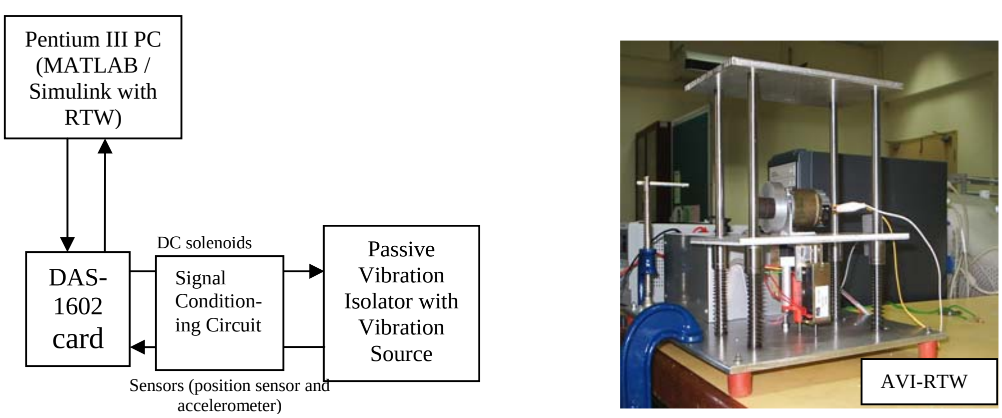


Fig. 2: Schematic Diagram of An AFC Strategy

4. Active Vibration Isolator (AVI-RTW)

The design of an active vibration isolator experimental rig or AVI-RTW is based on the working principle of active vibration control through cooperating sensors, actuators and control techniques within the mechanical structures. Fig. 3 shows the proposed design schematic for AVI-RTW rig using digital controller and the developed experimental rig. AVI-RTW is an integration of the mechanical parts, electric/electronic devices and computer control to make the rig functional as an active vibration isolator.



a) Block Diagram of the Proposed Rig

b) Developed Physical Experimental Rig, AVI-RTW

Fig. 3: Active Vibration Isolator (AVI-RTW) Rig

With the aid of MATLAB/Simulink software plus Real Time Workshop (RTW) feature and the use of a data acquisition card, DAS-1602 with the input and output devices connected, the practical AVI-RTW rig that integrates both the software and hardware elements was made possible.

4.1 Simulink with Real Time Workshop (RTW)

The crucial element in the development of the experimental rig is the Real Time Workshop (RTW) tool that is used together with the parent MATLAB and Simulink software. RTW enables ‘hardware in the loop feature’ that has an ability to execute the Simulink model in real-time via an interface card (I/O card) such as DAS-1602 used in this study. In other words, the main advantage of this feature is that it enables the user to execute the experimental study almost seamlessly just like simulation counterpart. Figure 4 shows the Simulink with RTW model used in the AVI-RTW rig that employs PID and AFC controllers. A switch is inserted into the model to accommodate the switching mode from PID to AFC vice versa. It should be noted that the AFC mode is actually a combination of AFC and PID controllers and thus it is sometimes denoted as AFC-PID scheme. The RTW model is in fact the representation of the physical active vibration isolator complete with the physical sensors and actuators connected to the DAS 1602 interface card and mechanical suspension structure.

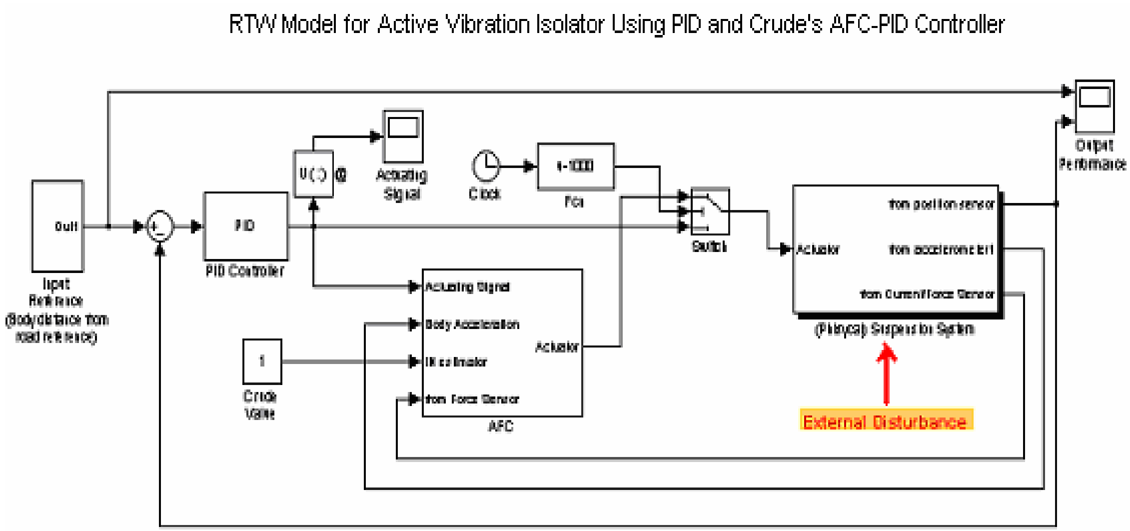


Fig. 4: The Simulink with RTW Model Using PID and/or AFC Controller

5. Experimental Results and Discussion

One of the main objectives of the experimental study is to obtain the best responses of each controller - PID and AFC by tuning the respective parameters of the controllers. For PID controller, the ‘best’ combination of proportional and derivative gains need to be tuned appropriately and this was typical performed using a trial-and-error approach. For AFC, besides tuning the parameters for PID controller, the estimated mass (M^*) of the system has to be appropriately approximated. In this study, a crude approximation method was used and the parameter was given a constant fixed value. The position, force and acceleration signals were measured using the sensors installed at suitable locations within the rig. The experiments were carried out considering three phases of forcing frequencies at 4, 24 and 40 Hz to observe the system responses. Figures 5, 6 and 7 show the comparison of mass displacement response of each active controller (PID and AFC) and without controller (passive system) at 4, 24 and 40 Hz respectively. The chosen parameters used in the experiment were assumed to be the best tuned parameters that give the best performance of each controller. The vibration source is in the form of an unbalanced rotating mass that is applied to the platform (mass). The rotational speed of the rotating mass constitutes the forcing frequency of the system.

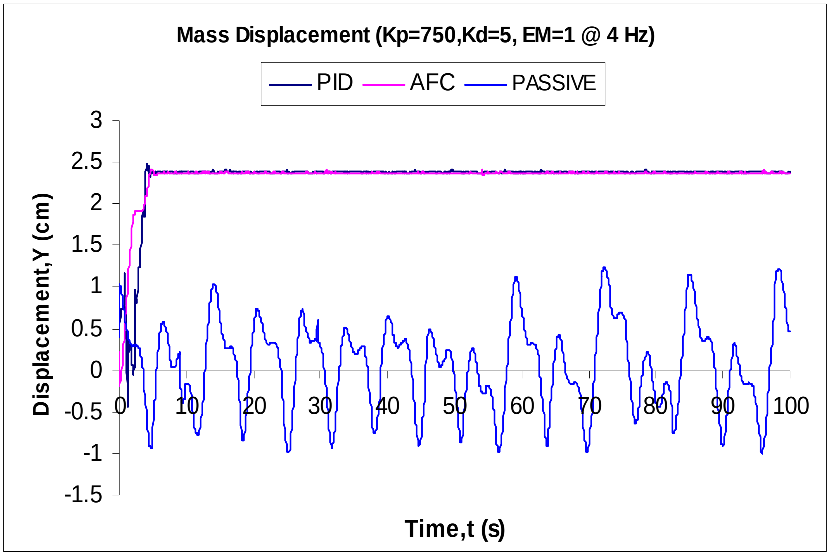


Fig. 5: Mass Displacement Response at 4 Hz

From Fig. 5, at 4 Hz, it was observed that PID and AFC controllers both produced almost the same performance in compensating the vibration effect. With vibration amplitude of approximately 2 cm peak-to-peak shown by the passive system, the PID and AFC control had successfully compensated the vibration effect by achieving more than 100% reduction in the amplitude. It can be seen from Fig. 5 that there is hardly vibration occur when active control methods (both PID and AFC controllers) were used at the steady state conditions. At 24 Hz, it was demonstrated that the AFC controller gives much better performance than the PID controller again in terms of the transient response where the former (AFC) produces faster settling time at 5 s in contrast to more than 17 s for the latter (PID) counterpart (Fig. 6). The vibration amplitude for this condition was at approximately 0.6 cm peak-to-peak. Again, both controllers have shown the capability to offset or suppress the vibration to nearly 98% in reduction. At much higher frequency (40 Hz), the performance of PID controller was significantly degraded and only managed to yield 4% reduction in vibration amplitude compared to about 40% reduction given by AFC controller as shown in Fig. 7. Thus, it is obvious that the AFC scheme provides the best overall performance and is consistently more robust compared to the PID scheme in terms of its capability to suppress vibration at various disturbance levels. Active controllers were by far the better performers than the passive counterpart to achieve the objective of the study.

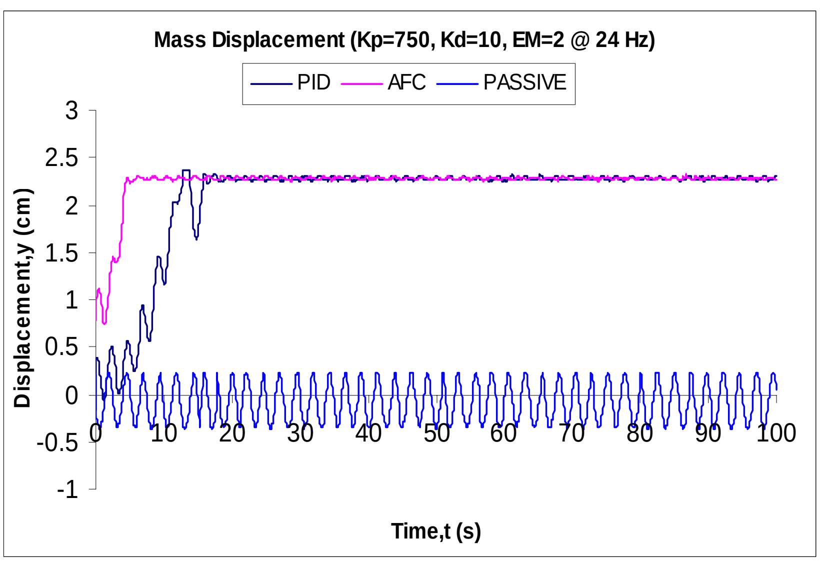


Fig.6: Mass Displacement Response at 24 Hz

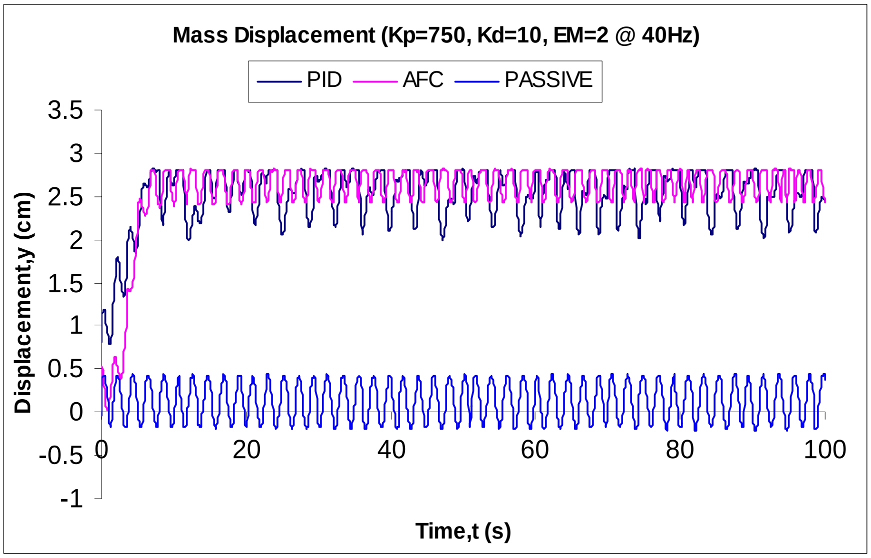


Fig. 7: Mass Displacement Response at 40 Hz

6. Conclusion

The experimental rig in the form of an active vibration isolator was successfully developed and experimented. The MATLAB/Simulink software with RTW feature and DAS 1602 interface card were the 'key-players' in the realisation of the AVI-RTW rig. From the results obtained, it is clear that the active vibration isolator using either PID or AFC controller gives a much better performance than the passive isolator. Overall, the AFC control scheme gives the excellent overall performance in compensating the disturbances (vibrations at various levels) introduced into the suspension system. This clearly demonstrates the robustness and potentials of the practical AFC scheme in that it can be readily implemented in real-time arising from the fact that the control algorithm is mathematically simple and computationally not intensive.

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